Mu2e Experiment at Fermilab: Calibration with Linac and Collimation System

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Abstract

Using a Monte Carlo simulation we modeled a linac beam passing through a collimation system. We modeled the interaction of relativistic electrons in a 1 cm thick tungsten collimator with a circular hole 1 μm in radius. Bremsstrahlung energy loss and scattering were simulated every tenth of a radiation length as a simulated electron traveled through the collimator. We found that an electron bunch of 10^9 particles could be reduced to about 389 undisturbed electrons. We compared the feasibility of using an upgraded version of the AØ photoinjector accelerator at Fermilab and a plasma wakefield accelerator as the electron source.

I. Background and Introduction

The Mu2e experiment will be looking for charged lepton flavor violation (CLFV) in the form of neutrinoless muon to electron conversions. The signal for such a conversion is a 105 MeV electron. Supersymmetric models predict this muon to electron conversion[2] which would not be explained by the Standard Model. This experiment may produce clues concerning the nature of Dark Matter.

We are studying a possible calibration technique for the Mu2e experiment in which electrons are injected into the downstream end of the detector. The calibration system is shown schematically in Figure 1. The intensity of an electron beam produced by a linac is reduced by a collimation system and momentum-selecting spectrometer. Electrons travel through a transport system to arrive at an injection port behind the Mu2e calorimeter.

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[2] The Mu2e Collaboration, *Mu2e Proposal*, Fermilab, Oct 10, 2008.

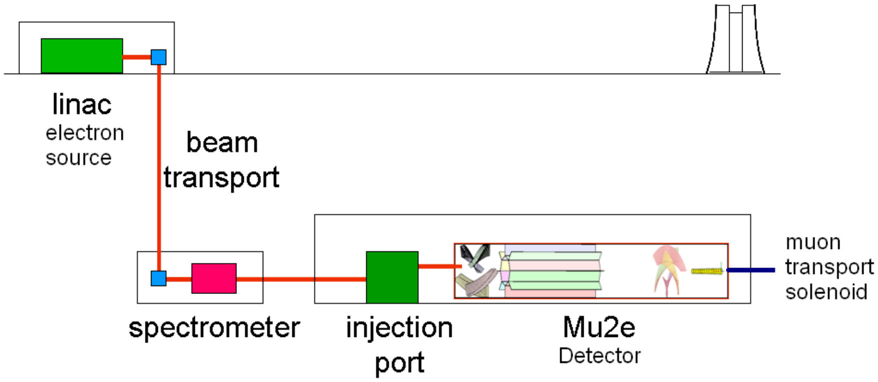

Figure 1. Schematic illustration of the calibration system.

This report focuses on the linac and collimation, illustrated in Figure 2. We also discuss use of a plasma wakefield accelerator as an alternative to an upgraded version of the AØ photoinjector as the source of 105 MeV electrons.

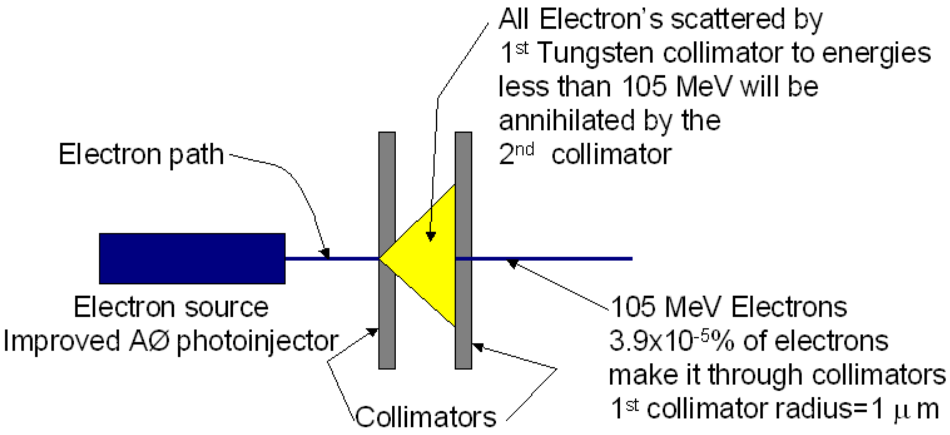

Figure 2. Linac and collimation overview.

II. Method

MATLAB[3] is used to simulate the 105 MeV electron beam coming from an upgraded AØ photoinjector[4] at Fermilab. Two collimators are located 10 meters and 12 meters from the linac. The first collimator is 1 cm thick tungsten with a circular hole 1 μm in

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[3] D. Hanselman, et al., *Mastering MATLAB 7*, 2005. See also R. Pratap, *Getting Started with MATLAB 7*, 2006

[4] A0 photoinjector parameters, http://www-ap.fnal.gov/A0PI/INJII_info.html

radius, while the second collimator is similar except for a 2.5 μm radius hole. The simulated linac beam contains 10^9 electrons in a bunch with normalized emittance ξ_n = 11 mm·mrad and $\sigma_{x,y}$=1mm RMS transverse size. Since the emittance[5] $\xi = \xi_n / \gamma$ is the product of the width and transverse angular spread of a beam, we derive the beam's angular divergence to be $\sigma_\theta = 5.35\times10^{-5}$ radians. $\left(\gamma \equiv E/mc^2 \approx 205.\right)$ These standard deviations $\sigma_{x,y}$ and σ_θ are used in the Monte Carlo simulation.

After the general geometry of the collimation was configured (see Figure 2), it was important to understand the interaction of electrons in tungsten as the beam interacted with the collimator. We assumed the energy of an electron after it traveled a distance *x* in tungsten was

$$E(x) = E_0 e^{-x/X_0}$$

where X_0 is the radiation length of tungsten. Both bremsstrahlung energy loss and scattering were simulated in one-tenth radiation length intervals as a simulated electron traveled through the collimator.[6] Scattering was described as a Gaussian process with RMS angular width

$$\theta_0 = \frac{13.6MeV}{\beta cp}\sqrt{\frac{x}{X_0}}\left[1+0.038\ln\left(\frac{-x}{X_0}\right)\right].$$

Here *p* is the electron momentum, initially taken to be 105 MeV/*c*.

We studied the possibilities of an electron nicking the entrance of the hole, the electron traveling partially through the solid tungsten only to be scattered back into the hole, and an electron entering the tungsten from inside the hole. Figure 3 illustrates the paths of electrons that entered the tungsten through the inside walls of the hole in the collimator.

Because of the small hole size and the large electron bunch radius, it was unnecessary (and impractical) to simulate electrons striking the upstream face of the collimator far from the hole. With Gaussian distributions on bunch size and divergence, we calculated how many electrons, N_{hole}, would pass undisturbed through the collimator:

$$N_{hole} = \frac{NA_{hole}}{2\pi\left(\sigma_x^2 + d^2\sigma_\theta^2\right)}.$$

Here *N* is the number of electrons per bunch (taken to be 10^9), A_{hole} is the area of the collimator hole, and *d* is the distance from the linac to the collimator.

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[5] M. Reiser, Theory and Design of Charged Particle Beams, 2nd Edition, 2008
[6] *Phys Let B*, 667, 2008

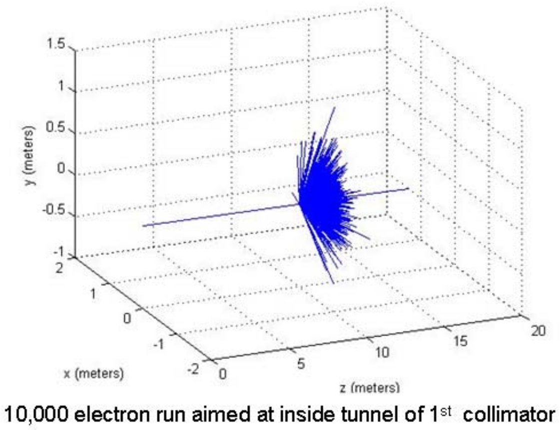

Figure 3. Paths of electrons which struck the inside wall of the hole in the collimator.

To learn about the prospects for use of a different technology electron source we spoke with Jérôme Faure (Laboratoire d'Optique Appliquée, France) about his group's experimental plasma wakefield accelerator.[7,8,9] From our conversation we believe that the parameters characterizing the LAO accelerator correspond to a larger angular divergence, but smaller spot size: $\sigma_\theta = 7\times10^{-3}$ radians and $\sigma_{x,y} \sim$ few microns. Perhaps the beam could be focused with quadrupole magnets. The feasibility of a plasma accelerator electron source is worthy of further investigation.

III. Results and Discussion

From the MATLAB Monte Carlo simulations it was easy to understand that the first collimator would eliminate most of the electrons. The major concern was if the electrons that scraped the collimator walls could participate in the calibration electron sample. Our simulations revealed that:

1. Electrons scraping the inside walls of the first collimator will lose energy and scatter so that 100% will be eliminated by the second collimator.
2. Electrons striking the upstream face of the first collimator close to hole will generally scatter and loose so much energy as to be eliminated by the second collimator.

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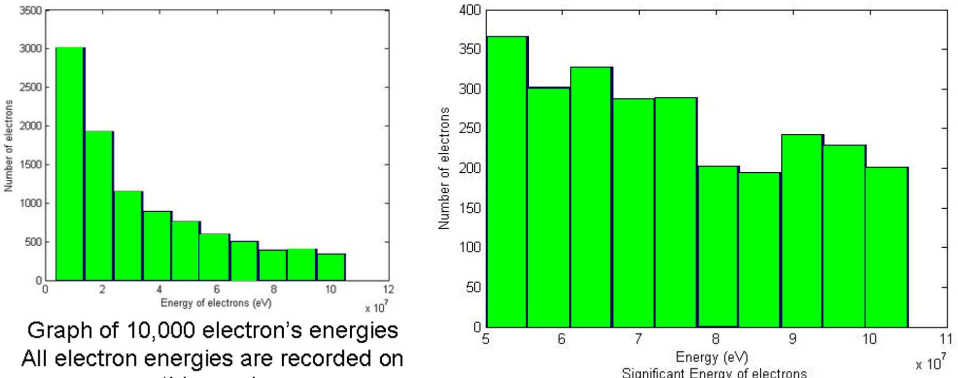
[7] C. Joshi, CERN Courier, 30148, 2007 http://cerncourier.com/cws/article/cern/30148
[8] C. Rechatin et al., *New J. Phys.* **11**, 103011, 2009
[9] J. Faure, Laboratoire d'Optique Appliquée, ENSTA, CNRS, Ecole Polytechnique, UMR 7639, 91761 Palaiseau, France, 2009

Figure 3 illustrates one of the simulation runs in which an electron beam was aimed at the inside wall of the hole in the first collimator. Since the beam distribution is Gaussian there were a few outliers that traveled cleanly through the collimator to keep their initial energy of 105 MeV. Here the first collimator is ten meters downstream of the linac while the second is two meters downstream of the second. (Only tracks of electrons with energies greater than 50 MeV are shown in this plot.)

Figure 4 shows histograms of the energy after the first collimator for electrons that struck the inside wall of the collimator. The left plot reveals that most of the electron energies are reduced below 50 MeV while the right plot includes only energies greater than 50 MeV. It is worth noting that all of these electrons are eliminated by the second collimator, as shown in Figure 3.



Graph of 10,000 electron's energies
All electron energies are recorded on this graph

Significant Energy of electrons
reduced by interaction in the matter of collimator

Figure 4. Energy of some electrons interacting in the first collimator.

	AØ photoinjector	Plasma wakefield
Angular divergence	5.35×10^{-5} rad	7.07×10^{-3} rad
Linac spot size	1×10^{-3} meters	few μm
Collimator radius	1×10^{-6} meters	1×10^{-3} meters
e^- with ~105 MeV after collimators	389 of 10^9	3 of 35000
e^- striking first collimator's walls	48 of 10^9	NA
e^- with energies > 50 MeV after interacting with the first collimator's walls	12 of 10^9	NA

Table 1: Comparison of AØ photoinjector and plasma wakefield accelerator results.

We ran similar simulations using the parameters obtained from Jérôme Faure for a plasma wakefield accelerator. Table 1 illustrates the comparison. The results are promising, and a plasma wakefield accelerator might be less expensive than an upgrade to the existing AØ photoinjector. The smaller spot size but larger beam divergence of the plasma accelerator may require focusing quadrupoles to be installed in the beamline.

IV. Conclusions

We have modeled a linac and two collimators as a possible electron source for a Mu2e calibration system. We find that electrons that interact with the first collimator are scattered and lose energy in such a way as to be eliminated by the second collimator. With the geometry described in this memo we estimate that 389 electrons out of a bunch containing 10^9 electrons produced by an upgraded AØ photoinjector would pass unimpeded through the collimators. The beam energy and emittance that can be obtained with plasma wakefield accelerators suggest that further investigation of this technology is warranted.

For more information about the calibration of the Mu2e detector see the papers by John Alsterda et al., Tim He et al., Guangyong Koh et al., McHugh et al., and Daniel Pershey et al. to be found in the Mu2e document database.

V. Acknowledgments

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